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Light Water Reactor Sustainability Program Seismic Data Gathering and Validation

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EXECUTIVE SUMMARY

Three recent earthquakes in the last seven years have exceeded their design basis earthquake values (so it is implied that damage to SSC's may have occurred). These seismic events were recorded at North Anna (August 2011, detailed information provided in [*Virginia Electric and Power Company Memo*]), Fukushima Daichii and Daini (March 2011 [TEPCO 1]), and Kaswazaki-Kariwa (2007, [TEPCO 2]). However, seismic walk downs following the earthquake at some of these plants indicate that very little damage occurred to safety class systems and components due to the seismic motion. This report presents seismic data gathered for two of the three events mentioned above and recommends a path for using that data for two purposes. One purpose is to determine what margins exist in current industry standard seismic soil-structure interaction (SSI) tools. The second purpose is the use the data to benchmark and validate seismic site response tools and SSI tools.

The gathered data represents free field soil and in-structure acceleration time histories. Gathered data also includes elastic and dynamic soil properties and structural drawings.

Gathering data and comparing with existing models has the potential to identify areas of uncertainty that may be removed from current seismic analysis and SPRA approaches. Removing uncertainty (to the extent possible) from SPRA's will allow NPP owners to make decisions on where to reduce risk. Once a realistic understanding of seismic response is established for a nuclear power plant (NPP), then decisions on needed protective measures, such as seismic isolation, can be made.

CONTENTS

ACRONYMS

DBE	Design Basis Earthquake
DOE	Department of Energy
INL	Idaho National Laboratory
NLSSI	NonLinear Soil Structure Interaction
NNSA	National Nuclear Security Administration
NRC	Nuclear Regulatory Commission
SASSI	System for Analysis of Soil Structure Interaction
SCDF	Seismic Core Damage Frequency
SI	Seismic Isolation
SSI	Soil-Structure Interaction

1. Introduction

Idaho National Laboratories (INL) has an ongoing research and development (R&D) project to remove uncertainties from seismic probabilistic risk assessments (SPRA) calculations using realistic modeling and simulation tools. These risk calculations should focus on providing best estimate results, and associated insights, for evaluation and decision-making.

SPRAs are intended to provide best estimates of the various combinations of structural and equipment failures that can lead to a seismic induced core damage event. However, in general this approach has large uncertainties built in that potentially mask other important events (for instance, it was not the seismic motions that caused the Fukushima core melt events, but the tsunami ingress into the facility).

The plan for development of advanced tools, methods for application in SPRAs is documented in *Coleman* (2014 (1)). In addition to developing tools and methodologies, it is important to use external hazard events that have already occurred at nuclear power plants (NPP) as case studies. Some recent seismic events that exceeded the design basis earthquake (DBE), also known as beyond design basis earthquake (BDBE), are:

- Seismic event recorded at North Anna (August 2011, detailed information provided in [*Virginia Electric and Power Company Memo*])
- Seismic and Tsunami events recorded at Fukushima Daiichi and Daini (March 2011 [TEPCO 1]),
- Seismic event recorded at Kaswazaki-Kariwa (2007, [TEPCO 2]).

These recent earthquake events offer unique opportunities to improve the state of practice for calculating seismic risk at NPPs. Some opportunities are:

- Recorded earthquake response data, both free field and in-structure, allows for development of more robust experience based seismic fragilities for some (SSCs). EPRI is gathering data from the three above-mentioned events to update SSC fragility curves. This data could also be used to evaluate seismic margins that exist in current nuclear power plant design basis.
- Advanced modeling and simulation tools and methods (Coleman and Spears 2014) are currently being developed at INL to perform nonlinear soil structure-interaction analysis (NLSSI). Seismic data gathered during the above-mentioned earthquakes could be used to validate these advanced tools.
- The recorded event data could be used in a case study to improve the current United States (US) SPRA methodology. A proposed case study plan is presented in Coleman (2014 (2)).
- Analyze the gathered data to determine if nonlinear effects are present. For instance if gapping and sliding between the soil and structure is dissipating energy than the recorded earthquake motion on the basemat of the structure should be lower than the recorded motion in a free-field location at the same elevation.
- Use data gathered at North Anna NPP to determine if high frequency ground motion travels into the structure. This is important since some linear soil-structure interaction (SSI) tools cannot propogate high frequency ground motion.

2. Gathered Data

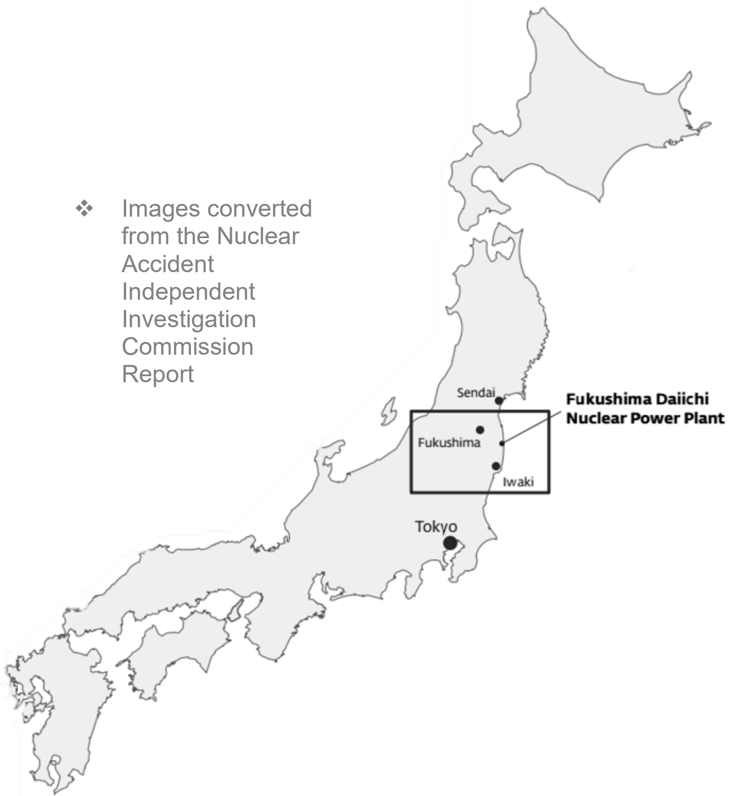
Data presented in this section of the report includes both recorded earthquakes at nuclear power plants (both free-field and in-structure), site-specific dynamic soil properties, and locations of the recorded data. Future research and development (R&D) applications of the data are discussed in each section.

Recorded earthquake data has been gathered from three recent earthquakes, North Anna (August 2011, detailed information provided in [Virginia Electric and Power Company Memo]), Fukushima Daichii and Daini (March 2011 [TEPCO 1]), and Kaswazaki-Kariwa (2007, [TEPCO 2]). The gathered data represents free field soil and in-structure acceleration time histories data. Gathered data also includes elastic and dynamic soil properties and structural drawings. Also presented in this section is recorded data gathered at Idaho National Laboratory (INL) site and also a discussion of the INL seismic monitoring program. The data is presented below.

2.1 Fukushima Daichii

2.1.1 Site Details

Fukushima Daiichi NPP is owned and operated by the Tokyo Electric Power Company (TEPCO). The facility is located on the Japanese coastline, surrounded by the cities of Fukushima, Iwaki, Minamisoma, Nihonmatsu, and Sendai. Figures 1 and 2 depict the location of Fukushima Daiichi relative to the country boarders.



- Images converted from the Nuclear Accident Independent Investigation Commission Report

Figure 1: The country of Japan outlining cities relevant to the Fukushima Daiichi NPP

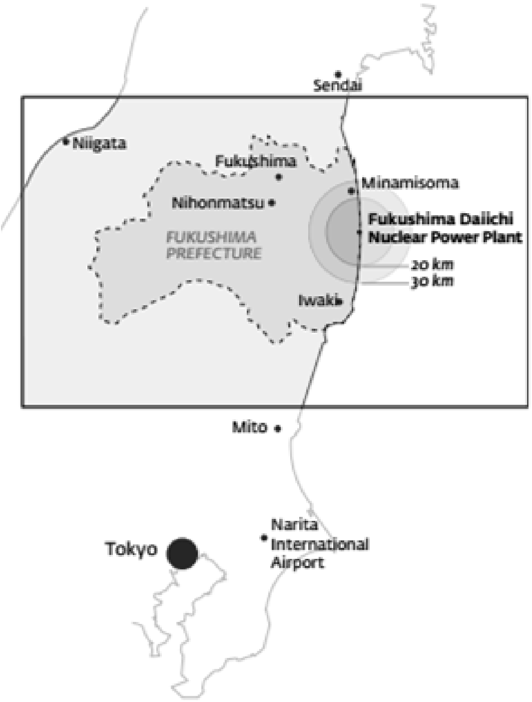


Figure 2: Magnifies the location of the Fukushima Daiichi NPP and surrounding areas

The nuclear facility consists of Reactor Units 1 through 6. Figure 3, provided by the NAIIC (2012) report, outlines in detail the layout of the Fukushima Daiichi NPP. The image was used to reference the location of the observation sites for the geotechnical analysis of the region.

- Image converted from the Nuclear Accident Independent Investigation Commission Report
- Adapted from: INPO "Special Report on the Nuclear Accident at the Fukushima Daiichi Nuclear Power Station"

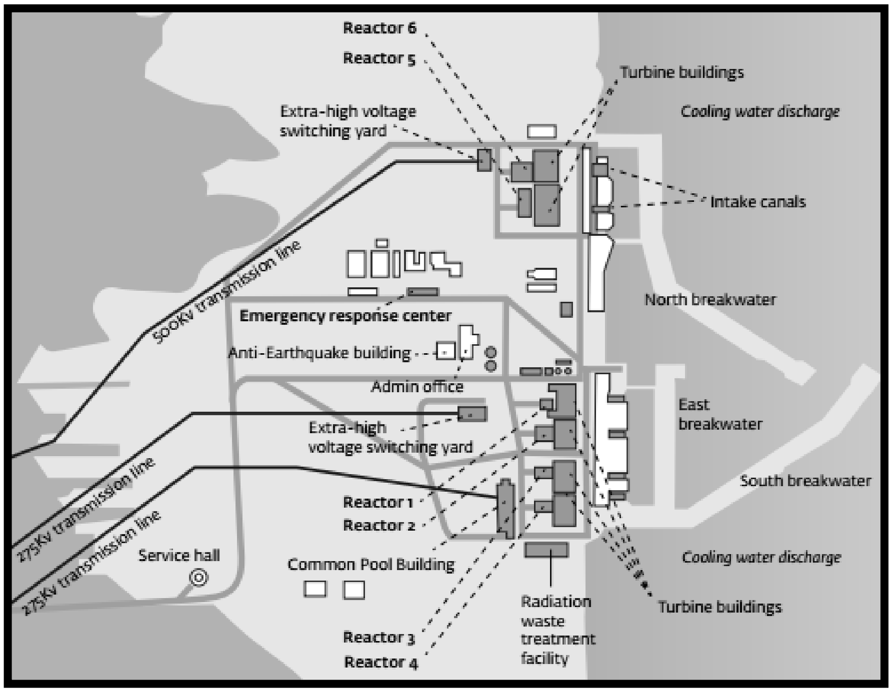
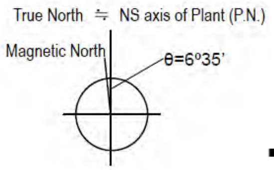


Figure 3: Layout of the Fukushima Daiichi Nuclear Power Plant

Four boreholes were drilled according to the TEPCO records. A free field borehole array was documented at the North and South points of the nuclear facility. Data was also monitored at boreholes near Unit 6, and Unit 5. Figure 4 displays the locations of the observation points on site where schematic information was retrieved.

The soil layers present at the site are depicted from the borehole information provided by TEPCO. There is uncertainty in the exact depth of a substratum level below the surface. The layer thickness, approximated depths, and observation points are projected in Figure 5. The soil description consists of alternating Sandy Loams, Mudstones, Gravel, Sandstones, and Fine Sands. More detail on the stratigraphy is noted in Figure 5 for defined soil layering.



- Image adapted from the TEPCO and the Association for Earthquake Disaster Prevention Records
- TEPCO CD-ROM

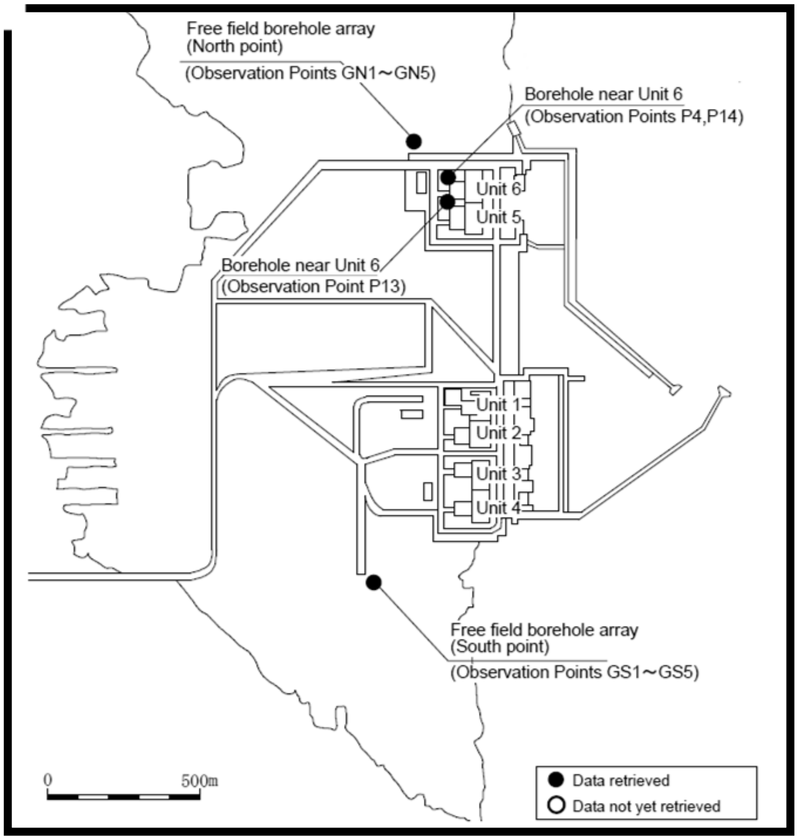


Figure 4: Fukushima Daiichi Nuclear Power Plant Schematic Location of Boreholes on Site

2.1.2 Site Soil Profile

The soil in this area is dominantly classified as variations of mudstone. The Geological Society specifies Mudstone as "—made of tiny clay particles. These tiny particles are deposited in quiet low energy environments like tidal flats and deep sea."

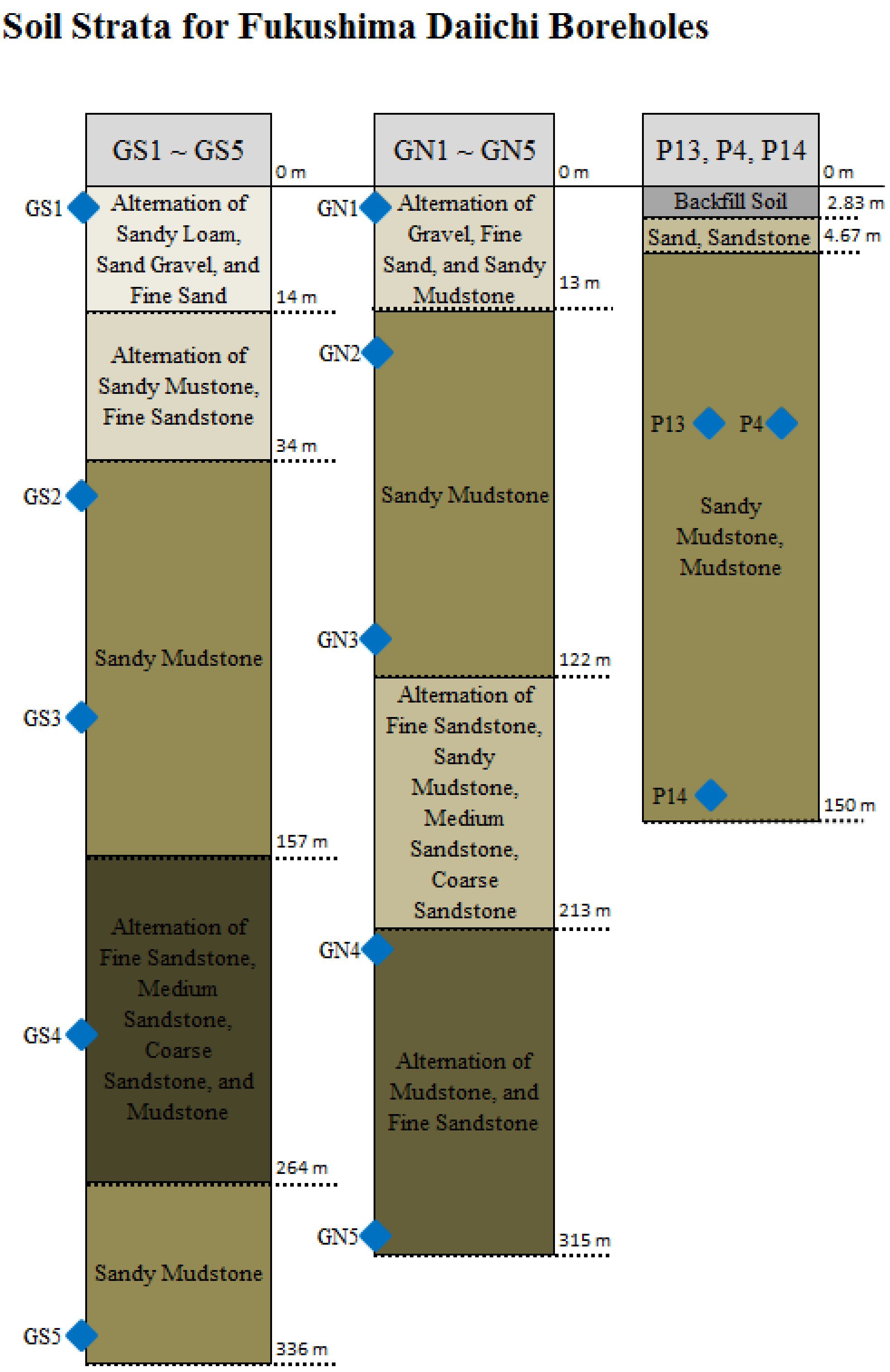


Figure 5: Interpreted Soil Layering for Boreholes Designated in Figure 4

2.1.3 Site Soil Material Properties

Seismic observation data and ground motion simulation files were purchased from TEPCO by INL. The information provided contains acceleration time histories and locations of the recorded motion. PDF files include locations and characteristics of seismometers and soil conditions at the nuclear power plant. Borehole locations are identified in Figure 4, above.

The geological stratum and location of seismometers at approximate depths and altitude were denoted in the TEPCO Fukushima Daiichi File #3 for the boreholes specified. Similarly, Elastic Wave Velocity diagrams were present for each borehole array. Figure 6 is an independent chart graph generated from the supplied TEPCO data. Original figures can be referenced from the TEPCO CD-ROM No. 1032 distributed by The Association for Earthquake Disaster Prevention.

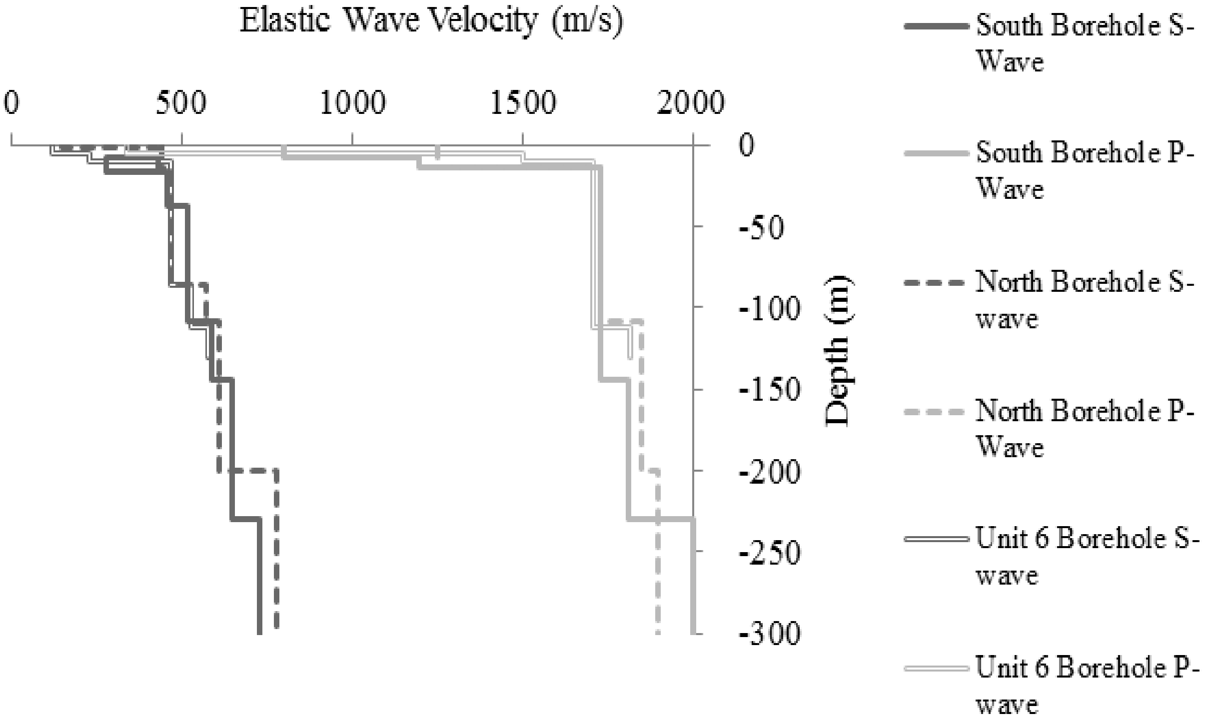
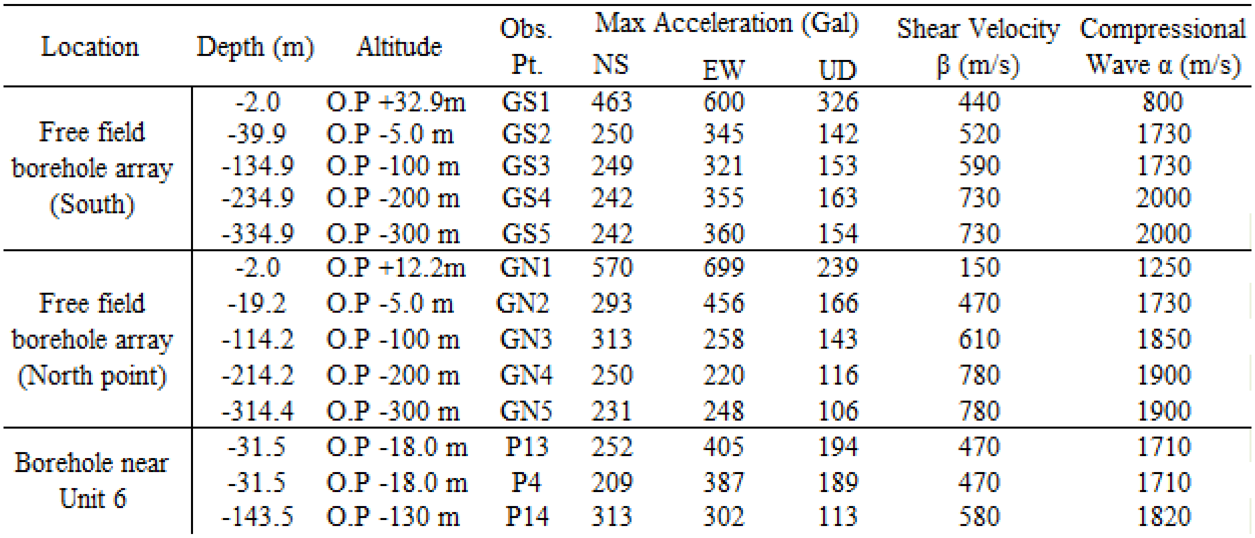


Figure 6: Elastic Wave Velocities for designated boreholes. Information utilized in TEPCO data files

Table 1 summarizes the provided data from the seismometers. The maximum recorded acceleration in north-south, east west, and up-down directions, shear wave, and compression wave velocities for each observation point are listed respectively in gals (cm/s^2) and m/s.

Table 1: Maximum Accelerations recorded in three directions for borehole locations



Location	Depth (m)	Altitude	Obs. Pt.	Max Acceleration (Gal) NS	EW	UD	Shear Velocity β (m/s)	Compressional Wave α (m/s)
Free field borehole array (South)	-2.0	O.P +32.9m	GS1	463	600	326	440	800
	-39.9	O.P -5.0 m	GS2	250	345	142	520	1730
	-134.9	O.P -100 m	GS3	249	321	153	590	1730
	-234.9	O.P -200 m	GS4	242	355	163	730	2000
	-334.9	O.P -300 m	GS5	242	360	154	730	2000
Free field borehole array (North point)	-2.0	O.P +12.2m	GN1	570	699	239	150	1250
	-19.2	O.P -5.0 m	GN2	293	456	166	470	1730
	-114.2	O.P -100 m	GN3	313	258	143	610	1850
	-214.2	O.P -200 m	GN4	250	220	116	780	1900
	-314.4	O.P -300 m	GN5	231	248	106	780	1900
Borehole near Unit 6	-31.5	O.P -18.0 m	P13	252	405	194	470	1710
	-31.5	O.P -18.0 m	P4	209	387	189	470	1710
	-143.5	O.P -130 m	P14	313	302	113	580	1820

The elastic properties were determined for the subsurface by referencing the Central Federal Lands Highway geophysical methodology. Equations 1 through 4, below, were utilized to determine the elastic constants from the shear wave and compressional wave velocities seen in Figure 6, above, and Table 1, above.

Equation 1 $$\nu = \frac{VP^2 - 2VS^2}{2(VP^2 - VS^2)}$$

Equation 2 $$E = \rho VS^2 \left[\frac{3VP^2 - 4VS^2}{VP^2 - VS^2}\right]$$

Equation 3 $$G = \frac{E}{2(1+\nu)}$$

Where E is the Young's Elastic Modulus (unit in Pascals), G is the Shear Modulus (unit in Pascals), ρ is the density of the soil (unit in kg/m3), ν and is Poisson's Ratio (unitless)

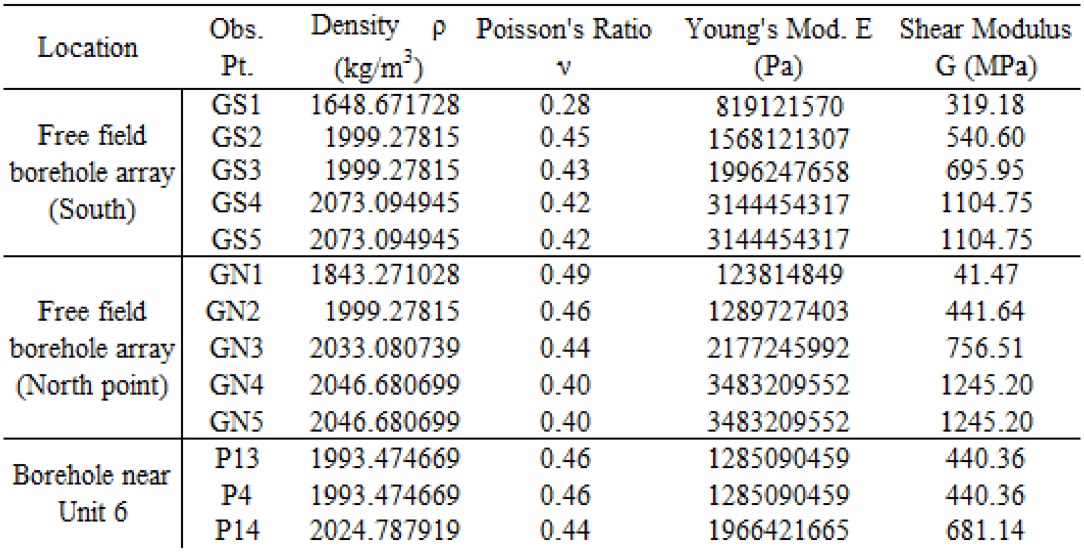
It is noted that the density for the soil was not provided in the TEPCO files. Density is a parameter necessary for evaluating seismic data and formulating elastic properties from shear and compressional velocities. To estimate adequate densities for the Fukushima Daiichi area, Gardner's Empirical Relationship was used to determine the dynamic density in the soil stratum.

Equation 4 $$\rho = a\, VP^x$$

Where a & x are constants equaling 0.31 and 0.25 respectively, and VP is the compressional wave velocity (unit in m/s)

Table 2 displays the calculated results for the elastic properties at the observation points in the borehole locations identified in Figure 4, above.

Table 2: Elastic Properties for observation points



Location	Obs. Pt.	Density ρ (kg/m^3)	Poisson's Ratio ν	Young's Mod. E (Pa)	Shear Modulus G (MPa)
Free field borehole array (South)	GS1	1648.671728	0.28	819121570	319.18
	GS2	1999.27815	0.45	1568121307	540.60
	GS3	1999.27815	0.43	1996247658	695.95
	GS4	2073.094945	0.42	3144454317	1104.75
	GS5	2073.094945	0.42	3144454317	1104.75
Free field borehole array (North point)	GN1	1843.271028	0.49	123814849	41.47
	GN2	1999.27815	0.46	1289727403	441.64
	GN3	2033.080739	0.44	2177245992	756.51
	GN4	2046.680699	0.40	3483209552	1245.20
	GN5	2046.680699	0.40	3483209552	1245.20
Borehole near Unit 6	P13	1993.474669	0.46	1285090459	440.36
	P4	1993.474669	0.46	1285090459	440.36
	P14	2024.787919	0.44	1966421665	681.14

Dynamic soil testing is important for deriving material properties used as input to Finite Element Analysis (FEA). Dynamic soil testing data for the Fukushima site is not publically available. Therefore the dynamic soil properties for the Fukushima site were derived from the publicly disclosed report titled Reduction of static and dynamic shear strength due to the weathering of mudstones (Yasuda 2012). This report documents dynamic soil properties for a site in Makinohara, Japan, approximately 464 kilometers south of the Fukushima Daiichi Nuclear Power Plant. Laboratory testing of soil at Makinohara concluded and classified the site as primarily Mudstone, the dominant soil present at the Fukushima site.

Figures 7 and 8 depict the dynamic soil data interpreted from the Yasuda (2012). The graphs are viewed as linear log plots. Cyclic torsional shear and triaxial tests were implemented to determine the dynamic behaviors of the soil site. This data could be used as input to linear or nonlinear time domain seismic soil structure interaction numerical models.

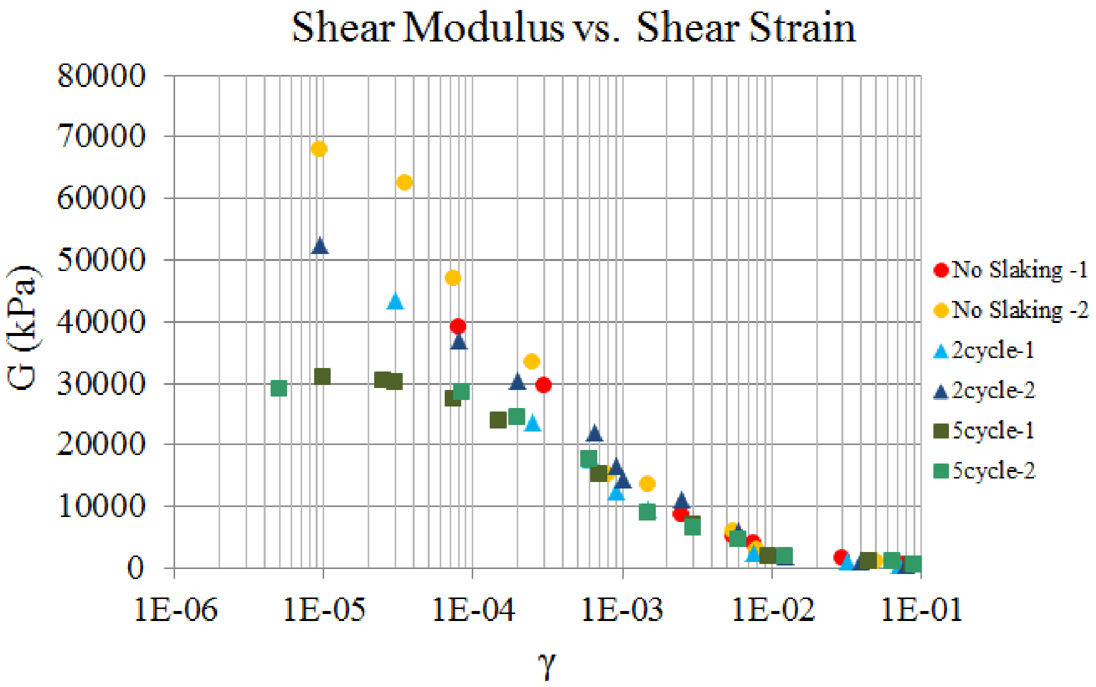


Figure 7: Shear Modulus versus the Shear Strain relationship. Where G is the shear modulus (unit in kPa), and γ is the shear strain (in/in). Please reference assumptions, below.

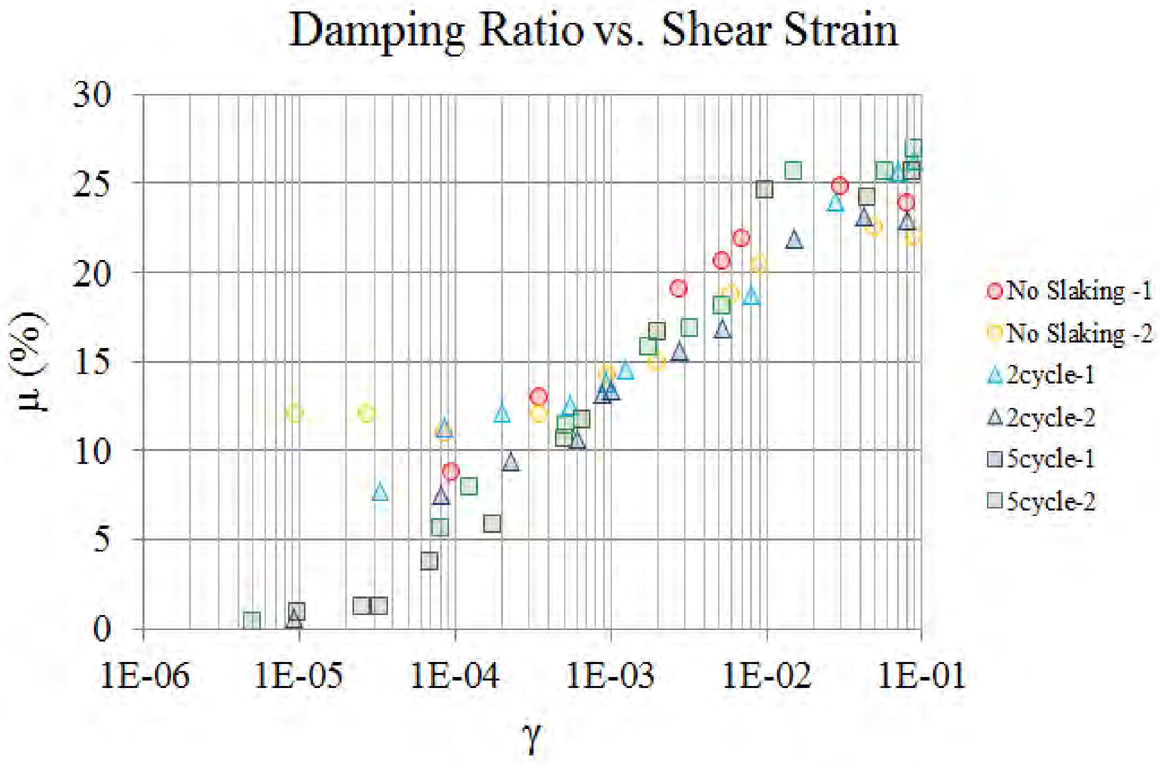


Figure 8: Damping Ratio versus the Shear Strain relationship. Where μ is the damping ratio (unit in %) and γ is the shear strain (in. /in.). Please reference assumptions, below.

2.1.4 Structural Drawings

Data is presented below for Fukushima units 1 and 6. Unit 1 is a BWR/3 with Mark I containment and Unit 6 is a BWR/5 with a Mark II containment (Table 3).

Table 3: Fukushima Daiichi reactor type (Information from G.E. Technology Advanced Manual)

Reactor type → **Fukushima Daiichi Unit →** **Reactor function ↓**	**BWR/3** **1**	**BWR/4** **2, 3, 4, 5**	**BWR/5** **6**
Reactor isolation pressure control	Isolation condenser and SRVs	All use SRVs. Some have steam condensing mode of RHR	All use SRVs. Some have steam condensing mode of RHR
Reactor isolation inventory control	Isolation condenser	RCIC	RCIC
ECCS high pressure pumping	HPCI	HPCI	HPCS
ECCS high pressure pump type	Turbine driven HPCI	Turbine driven	Motor driven
ECCS low pressure flooding delivery point	Recirculation pump discharge pipe	Recirculation pump discharge pipe or inside shroud (core region)	Inside core shroud, core region
Containment type	Mark I	Mark I	Mark II

Cross sectional views of units 1 and 6 and locations of seismometers are shown in Figures 9 and 10 below.

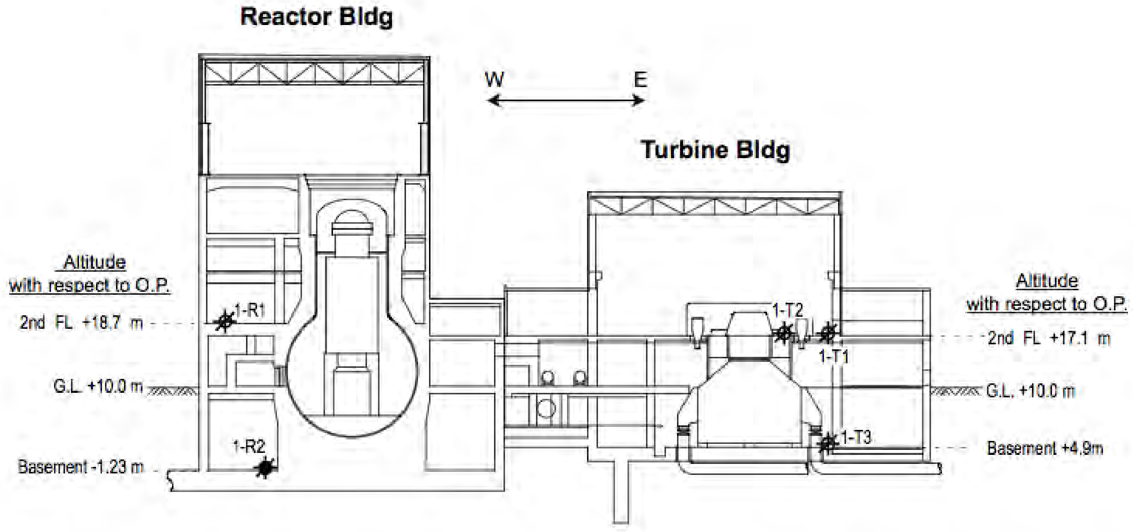


Figure 9: Cross-section view of Unit 1 and location of seismometers

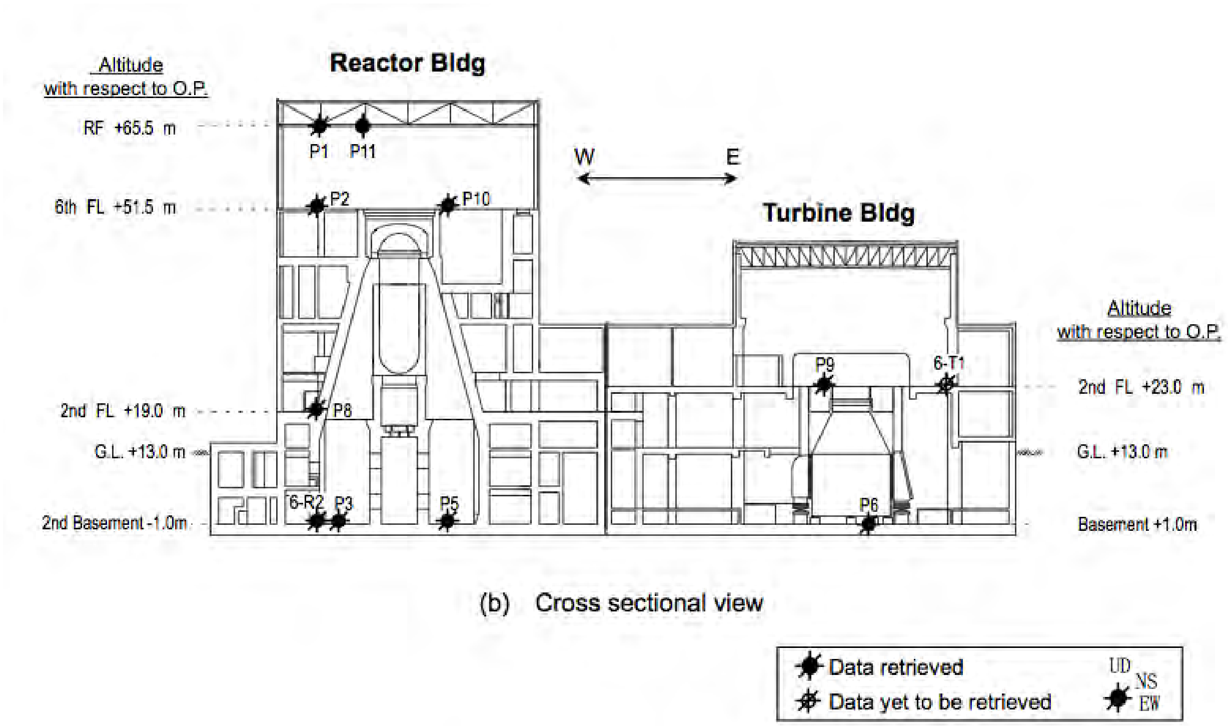


Figure 10: Cross-section view of Unit 6 and location of seismometers

2.1.5 Maximum Recorded Acceleration

Data gathered and presented in Table 2 above is presented for four locations in Table 3. These four locations were chosen at relatively the same location vertically, two free-field points and one point on the basemat of unit 1 and one point on the basemat of unit 6. The purpose of this is to infer if there is a reduction in the recorded maximum acceleration between the free-field motion and basemat motion. A reduction in maximum-recorded acceleration may indication that gapping and sliding between the soil and basemat is dissipating energy and therefore nonlinear effects are important. Figures 11 and 12 present the data comparison.

Table 3: Location of four points used for comparison to infer if nonlinear gapping and sliding occurred

Location	**Point Id**	**Location Vertically**	**Max acceleration (Gal)**		
			NS	EW	UD
Unit 1	1-R2	-1.23 m	460	447	258
Unit 6	P3	1m	290	431	163
Free Field (South Points by Unit 1)	GS1	-2 m	463	600	326
Free Field (North Points by Unit 6)	GN1	-2 m	570	699	239

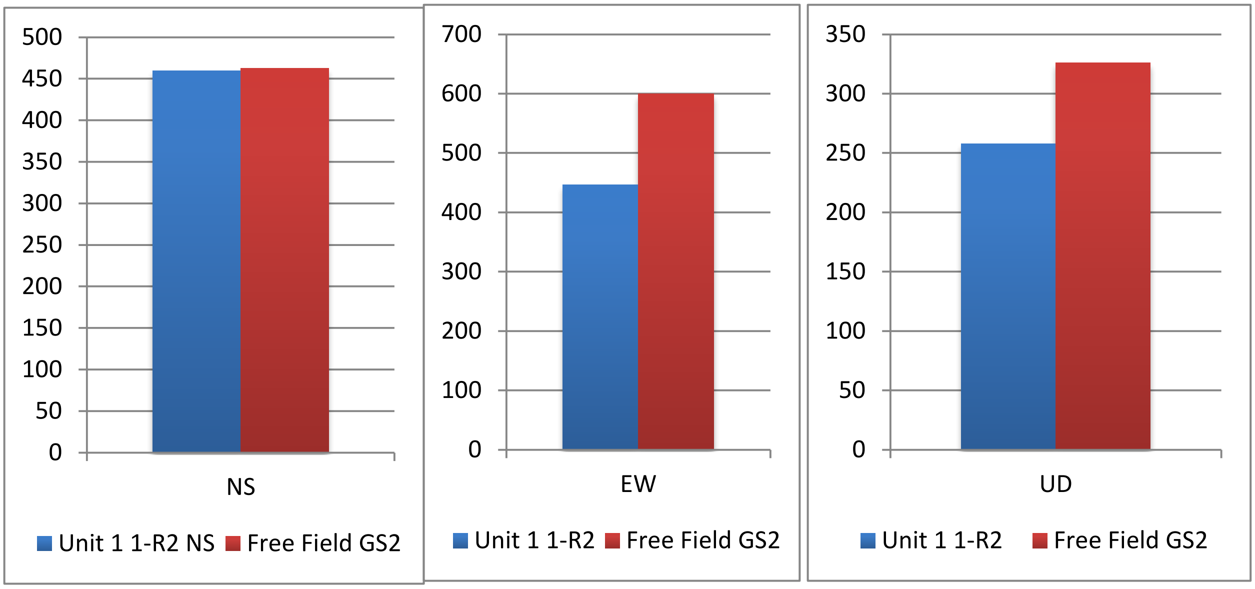


Figure 11: Maximum recorded acceleration value comparison between unit 1 basemat and free field location

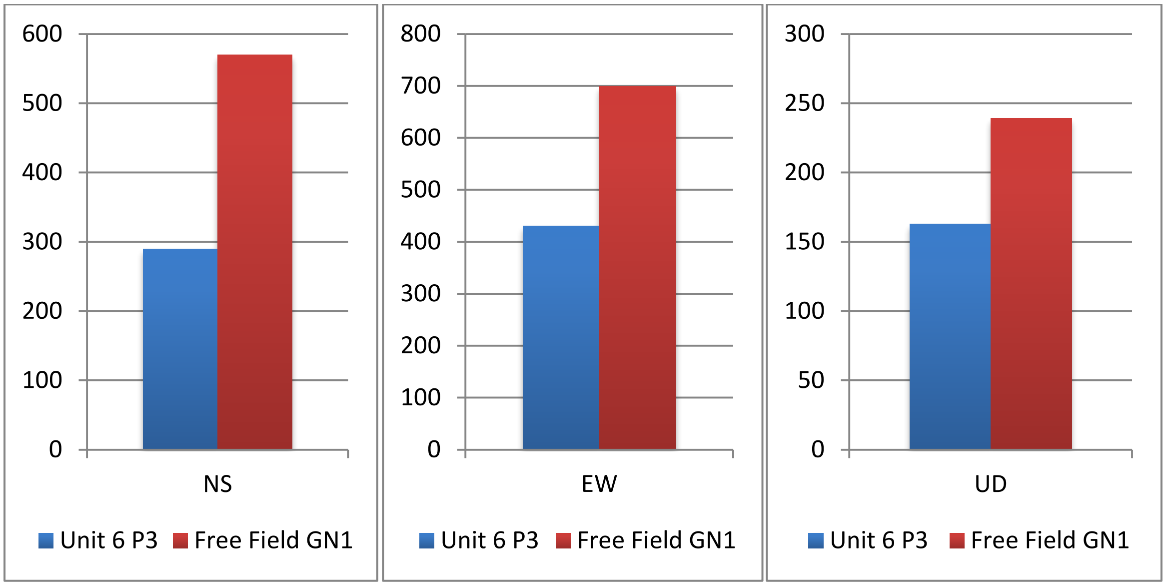


Figure 12: Maximum recorded acceleration value comparison between unit 6 basemat and free field location

2.1.6 Future Research and Development Application

The data gathered at Fukushima Daichii presents an opportunity to use in benchmarking 3D site response and nonlinear soil-structure interaction tools. One very interesting observation is the reduction in maximum acceleration between the free field recordings and basemat locations on unit's 1 and 6. The reduction in maximum accelerations seems to indicate that seismic energy is being dissipated at the interface near where the soil and structure are in contact. This could be both nonlinear soil behavior and geometric nonlinear behavior due to gapping and sliding.

2.2 Kaswazaki-Kariwa

Some information presented in this section is taken from IAEA-TECDOC-1722. The Kashiwazaki-Kariwa (K-K) Nuclear Power Plant (NPP) site is located in Kashiwazaki city and Kariwa town in Niigata Prefecture on the west coast of Japan (Figure 13).

The K-K NPP site has seven units (Figure 14) with five reactors that are Boiling Water Reactor (BWR) and two reactors that are Advanced Boiling Water Reactor (ABWR). A large earthquake was recorded at K-K in 2007.

The Niigataken-chuetsu-oki (NCO) earthquake occurred at 10:13 local time on 16 July 2007 with a moment magnitude of 6.6 and at a depth of 10 km near the West Coast of Honshu, in Japan. The hypocenter of the earthquake was below the seabed of the Jo-chuetsu area in Niigata prefecture. The epicenter was 70 km away from Niigata, Honshu, Japan.

Figure 13: Location of K-K NPP site (TEPCO).

Figure 14. Picture of the K-K NPP site (TEPCO).

Seismometers were installed both inside the units and in free field locations. Figure 15 shows the location of the seismometers. Figure 16 shows the locations for the free field bore holes and the unit 5 seismometers.

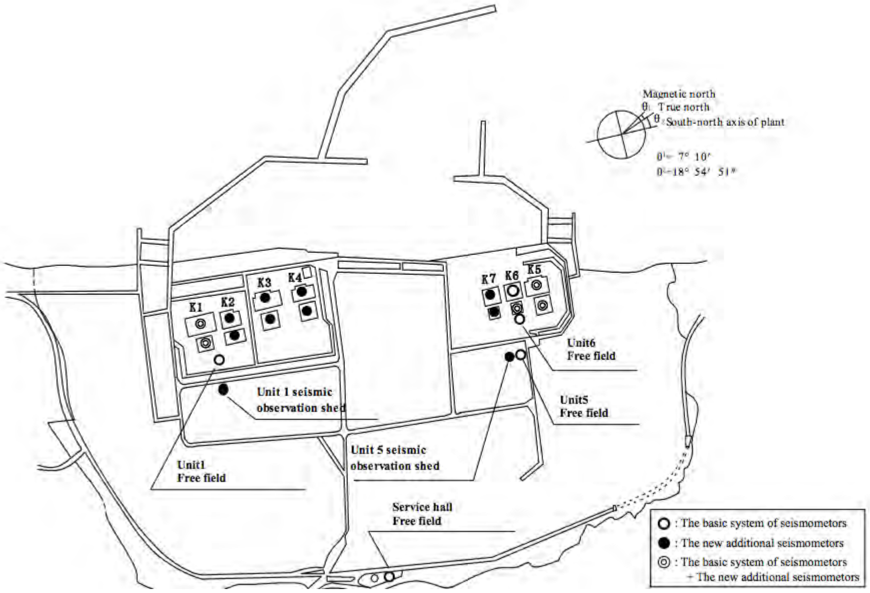


Figure 15: Locations of installed seismometers at the K-K NPP

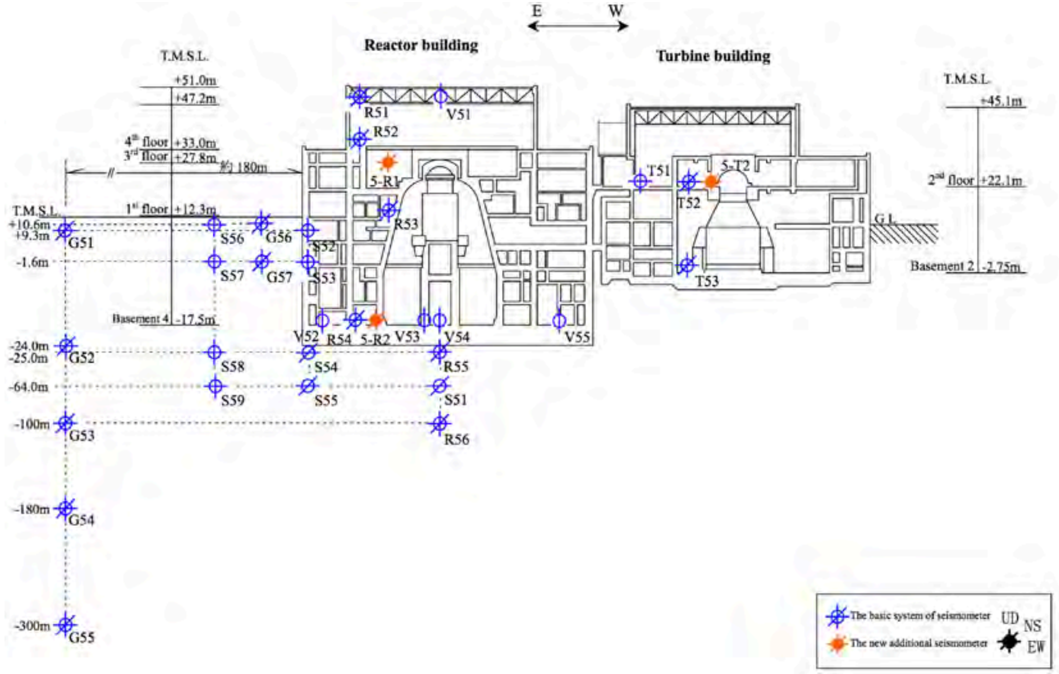
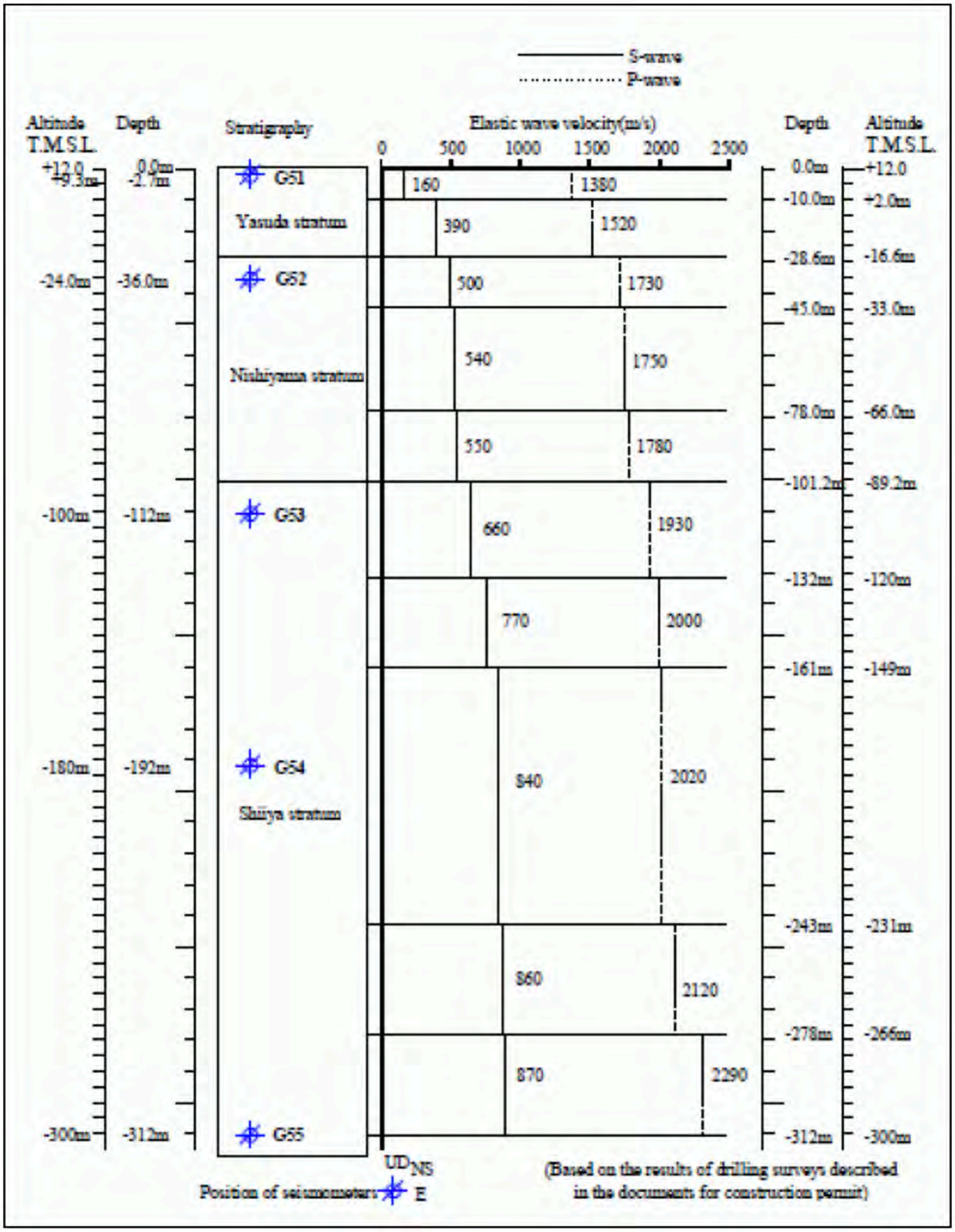


Figure 16: Cross section view of unit 5 and free field borehole locations

2.2.1 Site Soil Profile

Soil properties along the unit 5 free field borehole, G5, are presented in Figure 17. The borehole is 312m deep. Strain dependent G/G_0 and damping ratio for sand, clay and rock used for numerical analysis of the K-K site are provided in Figure 18.



(Based on the results of drilling surveys described in the documents for construction permit)

Figure 17: Free field borehole G5 elastic and dynamic soil data (IAEA-TECDOC-1722)

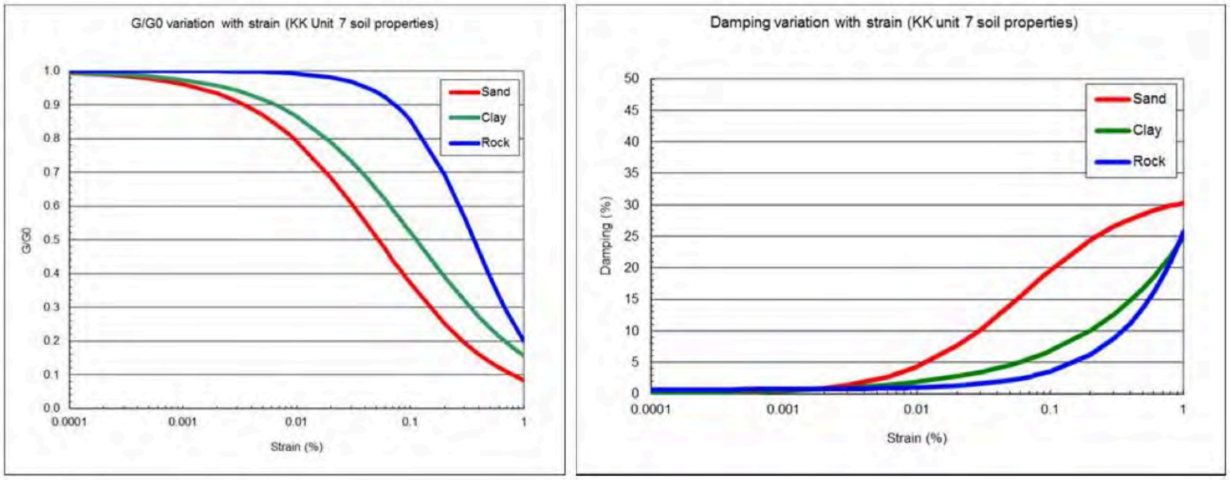


Figure 18: Dynamic soil property data used for numerical analysis of the K-K site (IAEA-TECDOC-1722)

2.2.2 Maximum Recorded Acceleration

Four in-structure maximum acceleration points are compared with one free field point at approximately the same location vertically (Table 4). The purpose of this is to infer if there is a reduction in the recorded maximum acceleration between the free-field motion and basemat motion. A reduction in maximum-recorded acceleration may indication that gapping and sliding between the soil and basemat is dissipating energy and therefore nonlinear effects are important. Figure 19 presents the data graphically for comparison. This comparison shows significant reduction in the north-south (NS) direction, some reduction in the east west (EW) for some units, and an increase in the up-down (UD) direction. The reduction is likely due to nonlinear dissipation of energy. The increase vertically could be due to impact energy generated due to vertical interaction between the soil and structure.

Table 4: Location of four points used for comparison to infer if nonlinear gapping and sliding occurred

Location	**Point Id**	**Location Vertically**	**Max acceleration (Gal)**		
			NS	EW	UD
Unit 1 Basemat	1-R2	-32.5	311	680	408
Unit 2 Basemat	2-R2	-32.5	304	606	282
Unit 3 Basemat	3-R2	-32.5	308	384	311
Unit 4 Basemat	4-R2	-32.5	310	492	337
Free Field	SG3	-31.9 m	403	647	174

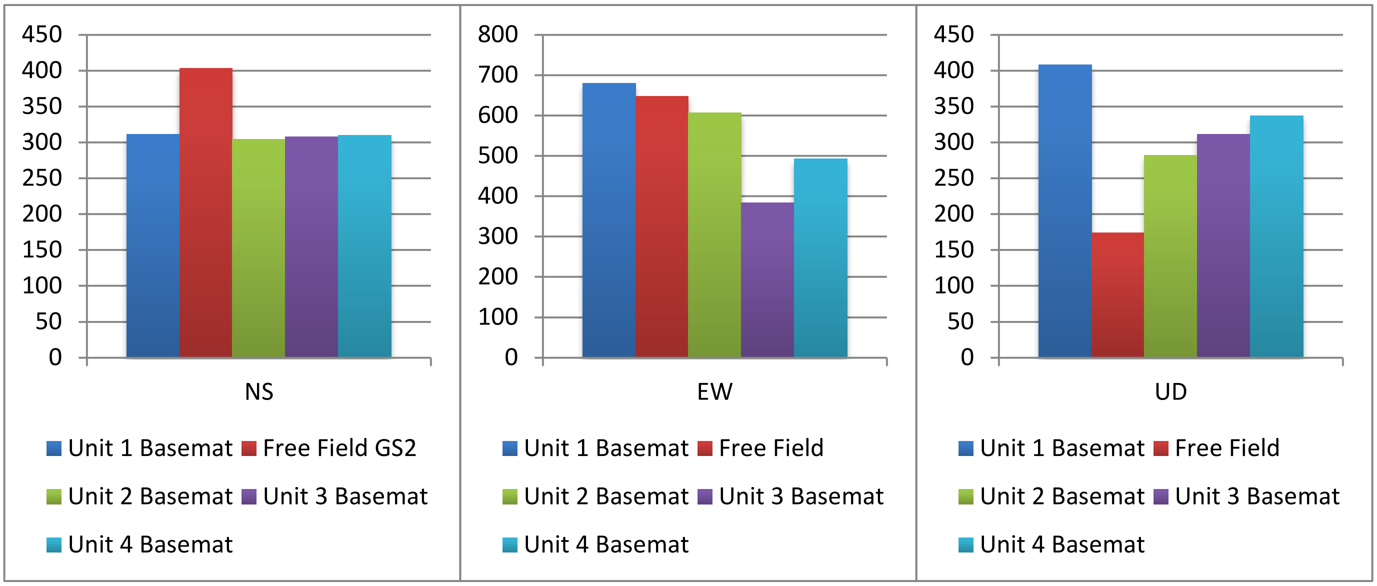


Figure 19: Comparison of maximum acceleration values recorded in the free field locations with those recorded in-structure on the basemat.

2.2.3 Future Research and Development Application

The data from K-K has been used in a benchmark study to determine if existing soil-structure interaction numerical codes could match the recorded event. That research is documented in, IAEA-TECDOC-1722. However if future benchmark exercises are performed using this data it is recommended that the study is probabilistic and realistic. This is due to large variation in soil material properties and the need to capture nonlinear material and nonlinear geometric behavior.

This gathered data could be used to further evaluate the importance of including geometric nonlinearities (gapping and sliding) in soil-structure interaction analysis for site with large seismic hazards. A rigorous probabilistic study could be used to evaluate how much energy is dissipated at the interface between the soil and structure.

2.3 North Anna

The North Anna NPP is operated by the Virginia Electric and Power Company (VEPCO) and consists of two pressurized water reactor units. The Mineral Earthquake on August 23, 2011 was recorded at the North Anna NPP. Following the earthquake both units were safely shut down. Post-earthquake investigations at the power plant confirmed that there was no significant damage to either safety-related or non-safety-related structures occurred during the earthquake (Graizer et al 2013).

The North Anna Earthquake caused the first instance of an operating reactor in US to exceed its design limit for ground acceleration, DBE (0.18 g for horizontal motion, structure on soil), peak recorded ground acceleration, 0.26 g.

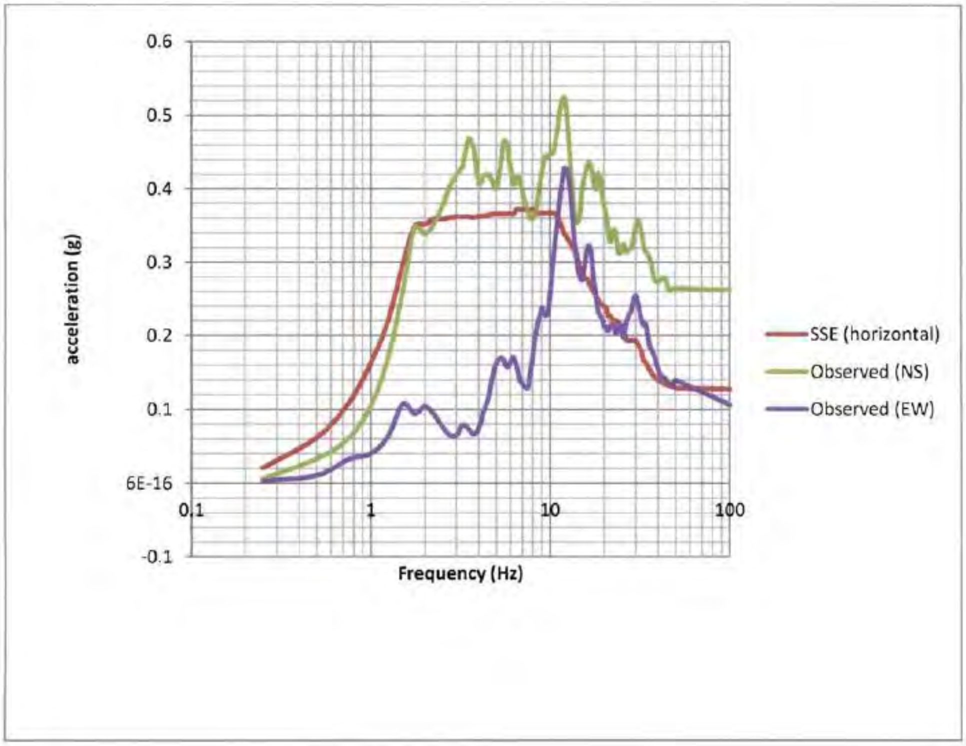


Figure 20: Comparison of horizontal response spectra at basemat floor level of North Anna NPP with its safe shutdown earthquake (SSE)

Data gathered at the North Anna NPP in-structure indicates high frequency response (around 30 Hz) propagates into the structure. The high frequency response has potential to damage equipment. This is important because linear and equivalent linear codes use strain compatible soil properties derived from software programs that use the theoretical wave equation that use smooth hysteretic loops to develop these properties. These hysteresis loops will not propagate high frequency response. The North Anna data indicates the necessity of using software programs that can propagate high frequency response.

2.4 INL

INL has gathered an enormous amount of data over the years, including recorded seismic events and borehole data to characterize the site-specific soils.

2.4.1 INL Seismic Monitoring Program

INL's Seismic Monitoring Program provides INL with earthquake data and staff expertise in support of seismic safety. This program documents earthquake activity on and around the eastern Snake River Plain in the vicinity of the INL. To achieve this, the INL maintains and operates 27 seismographs, 32 strong-motion accelerographs, and 13 Global Positioning System (GPS) stations. INL uses gathered earthquake data to evaluate seismic hazards.

Data collected by the INL seismic stations provide information on earthquake sources (such as locations, magnitudes, depths, fault dimensions, faulting style, and stress parameters), crustal structure, rock properties, and energy dissipation (or attenuation) characteristics of the subsurface. The INL strong-motion accelerographs determine the levels of earthquake ground shaking and responses of buildings to ground shaking. The GPS data helps identify active regions of more frequently damaging earthquakes relative to less active regions. Additional information on INL seismic monitoring program can be found at: http://quakes.inl.gov/monitoring/index.php

2.4.2 INL Site Specific Borehole Data

INL has approximately seven deep boreholes (with depths ranging from 2000ft to 10,000ft) and 370 shallow boreholes (with depths ranging from 18ft to 140ft). A summary of the documents that present the locations, lithography and soil properties of these boreholes, is provided in Table 4.

Table 4. Summary of available data

Report	**Author, year**	**Data**
INEEL/EXT-03-00943	S. J. Payne, 2006	362 boreholes V_S and ρ profiles for some of these sites Detailed lithography
--	--	V_S and V_P profiles from 8 shallow boreholes near IWTU Detailed lithography Borehole IDs: B-31, 33, 39, 41-II, 34-II, 35-II, 37, 38
INL/EXT-05-01047	S. J. Payne, 2007	Artificially constructed V_S, V_P and ρ profiles for 4 deep drill holes Drill hole IDs: INEL-1, WO-2, 2-2A, CH-1
DOE/USGS report: DOE/ID-22220	Brian V. Twining, Roy C. Bartholomay and Mary K. V. Hodges, 2012	Detailed lithography Drill hole ID: USGS 136
DOE/USGS report: DOE/ID-22229	Brian V. Twining, Roy C. Bartholomay and Mary K. V. Hodges, 2014	Detailed lithography Drill hole ID: USGS 140, 141

A detailed lithography is available for almost all the boreholes. However, the shear wave velocity (V_s) and mass density (ρ) are only available for a few boreholes. Payne (2007) used the lithography and the available V_s and ρ data and constructed a shear wave velocity-depth and density-depth profiles for the Basalt and sedimentary interbeds found at the INL site. These relationships are helpful in constructing approximate density and shear wave velocity profiles for the boreholes where only lithography is available.

2.4.3 Current understanding and plans for future work

The available data can be used to construct approximate density and shear wave velocity profiles from the lithography of the numerous boreholes at the INL site. After a preliminary examination it appears that there could be significant three-dimensional effects at this site, since there is very little correlation between the soil profiles from different, but reasonably proximate, boreholes.

The INL data could be used to map the 3D topography of the INL site and evaluate the site effects on seismic hazard using 3D site-response analyses. The approximate density and shear wave velocity profiles of the various boreholes may be used for this purpose. This 3D profile could be used to test new 3D site response tools under development at INL and elsewhere.

3. Application of Data for Validation of Numerical Models

Gathering data and comparing with existing models has potential to identify areas of uncertainty that should be removed from current seismic analysis and SPRA approaches. Removing uncertainty (to the extent possible) from SPRA's will allow NPP owners to make decisions on where to reduce risk. Once a realistic understanding of seismic response is established for a nuclear power plant (NPP) then decisions on needed protective measures, such as seismic (SI), can be made.

4. Long Term Vision and Implementation

INL is performing R&D activities that will develop an advanced nonlinear soil-structure interaction methods and advanced SPRA methodology. These methodologies will focus on using realistic numerical models to provide risk informed results.

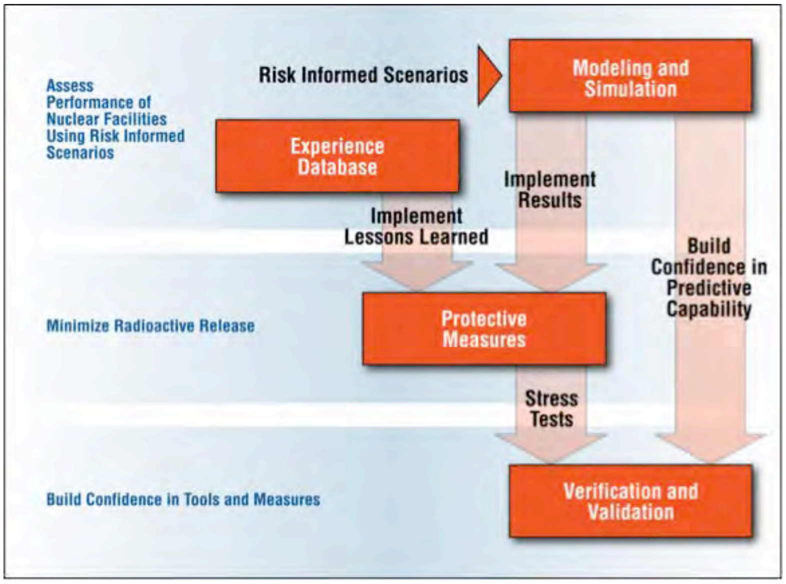


Figure 21: Future risk informed process to minimize radioactive releases to acceptable levels and manage risk

Future risk evaluations should follow a process similar to that shown in Figure 21. This process would start with risk informed external event scenarios such as seismic, flood, fire, tsunami, or a combination of these as initiating events. Verified and Validated (V&V) models would be used to simulate the external hazard initiators. Model results would be used to determine at risk systems and components and appropriate decisions made on what protective measures or mitigation could be needed. Of course implementation of experience data gathered from previous external hazard events at NPPs needs to be used in the decision making process.

Benchmarking and validation is an important part of numerical tool development since it demonstrates that the tools can match reality. Data gathered and presented in this report provides information that should be used to determine important physical behavior to model such as:

- Dissipation of energy between the soil and nuclear power plant foundation
- Nonlinear behavior of soil
- Models that can capture high frequency content in some ground motions, such as the motions recorded at the North Anna NPP during the Mineral Earthquake.

Some of the gathered data can also be used to validate seismic site response tools and nonlinear soil-structure interaction tools or used in case studies to evaluate SPRA decisions.

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